## Executive Summary
### Extracted from

### NIST NCSTAR 1-3 (Draft)

### Federal Building and Fire Safety Investigation of the World Trade Center Disaster

# Mechanical and Metallurgical Analysis of Structural Steel (Draft)

# EXECUTIVE SUMMARY

## E.1 OVERVIEW

The World Trade Center (WTC) towers collapsed on September 11, 2001, as a result of damage inflicted by aircraft and the ensuing fires. The properties of the steel played an important role in how the building performed, from the initial impact to the final collapse. Structural steel recovered from the site has been a valuable resource in the investigation of the disaster, providing information ranging from details of structural response to the aircraft impact to data on steel properties for insertion into models of building performance.

This report is an overview of the mechanical and metallurgical analysis of structural steel from the WTC, part of the National Institute of Standards and Technology (NIST) Investigation of the WTC disaster. The purpose was to analyze structural steel available from WTC 1, 2, and 7 to determine the metallurgical and mechanical properties and quality of the metal, weldments, and connections, and provide these data to other part of the NIST WTC Investigation for insertion into models of building performance. The analysis focused on steel from the towers to provide data for modeling building performance and characterizing the steel quality. In addition, the steel used in the construction of WTC 7 is described based solely on data from the literature, because no steel from the building was recovered.

The three goals were to:

1. Determine mechanical properties of WTC structural steel,

Determine the quality of the steel and if it met its design requirements, and

Analyze and provide insight into failure mechanisms for guiding the development of models of building performance and validating their output.

### E.1.1 Building Design and Steel Specifications

Building plans and material specifications from the construction era provided a starting point for the study. Thousands of pages of design documents were reviewed. Most valuable were the structural steel design drawings for the WTC towers provided by the Port Authority of New York and New Jersey. In addition, Laclede Steel Company, the fabricator of the floor trusses, provided construction-era documents that showed, amongst other information, that steels with higher strength than specified were used in the floor truss systems. Numerous other sources, including Yawata (now Nippon) Steel documents on perimeter column steel, provided essential insights into the steel fabrication and properties.

From the standpoint of building design, the towers were unique based on the number of different steels specified for construction. Fourteen different strengths of steel were specified in the design drawings, although only 12 were actually used. Most modern buildings use no more than two or three different strengths of steel.

Furthermore, more than a dozen suppliers and fabricators supplied steel for the buildings. As a result, even when the different steels met a single specification, their properties could be significantly different. These complications resulted in more than forty different steels being used in the tower structures, all of which are characterized to some extent in this study.

## E.2 INVENTORY OF RECOVERED STEEL

A total of 236 recovered pieces of WTC steel were cataloged; the great majority belonging to the towers, WTC 1 and WTC 2. These samples represented a quarter to half a percent of the 200,000 tons of structural steel used in the construction of the two towers. The NIST inventory included pieces from the impact and fire regions, perimeter columns, core columns, floor trusses, and other pieces such as truss seats and wind dampers.

The original, as-built locations of 42 recovered perimeter panels and 12 recovered core columns were determined, based on markings and geometry of the columns. Samples were available of all 12 strength levels of perimeter panel steel, the two strength levels of the core column steel that represented 99 percent of the total number of columns, and both strength levels used in the floor trusses.

A number of structural pieces were recovered from locations in or near the impact- and fire-damaged regions of the towers, including four perimeter panels directly hit by the airplane and three core columns located within these areas. These pieces provided opportunity for failure and other forensic analyses.

The collection of steel from the WTC towers was sufficient for determining the quality of the steel and, in combination with published literature, for determining mechanical properties as input to models of building performance.

## E.3 DAMAGE AND FAILURE MODES OF THE STRUCTURAL STEEL

Extensive failure analysis of the recovered steel was conducted to determine damage characteristics, failure modes, and fire-related degradation of the recovered structural components. In addition, pre-collapse photographic evidence of the impact damage and location and intensity of the fires was used to distinguish between pre- and post-collapse damage.

Two sets of observations were made:

1. Pre-collapse analysis concentrated on impact damage sustained by the perimeter panel sections. The analysis employed enhanced photographic and video images of the towers and was largely limited to the perimeter panels, because the core columns and most floor trusses are not visible in the images. The images were also used to determine the location of pre-collapse fires, damage to fire proofing, and possible fire-related damage to the panels. In addition, some details of pre-collapse, time-dependent deformation of the structure, including bowing of perimeter columns across wide areas of the perimeter walls, were characterized.

Post-collapse analysis concentrated on the damage characteristics of the recovered structural steel elements. The perimeter panels were again evaluated, as well as the core columns and the connectors or seat assemblies used to attach the floor trusses to the core columns and perimeter column panels. Of particular importance were the samples located near the airplane impact regions and those where fire was known to exist before the collapse of the buildings.

In addition to the NIST analysis, an outside contractor made an independent study of the recovered steel elements. In general, the observations concerning local failure mechanisms by the contractor agreed with those that NIST found.

The observations of fracture and failure behavior, described below, were used by the groups that modeled the building performance during impact and subsequent fire to guide the development of their models and validate their results.

### E.3.1 Structural Impact Damage – Perimeter Panels

Correlation between pre-collapse photographs and the recovered exterior panels from the impact zone indicates that two of the four recovered impact-damaged panels are in a condition similar to that just prior to building collapse. Some damage can be attributed to the events during and after collapse, but the general shape and appearance of the recovered pieces match the damage photographs.

The fracture behavior of the plates from the recovered columns that were hit directly by the aircraft was of particular interest. Transverse fractures of these plates (e.g., fracture through the outer webs of two impacted panels that occurred perpendicular to the rolling direction) exhibit ductile characteristics, including necking and thinning away from the fracture. These features indicate that the steel behaved in a ductile manner under very high strain rates.

Conversely, fractures that occurred parallel and directly adjacent to a welded joint exhibit little or no ductile characteristics. Diminished properties of the heat-affected zone in the base plate, the geometry of the joint with respect to the direction of impact, stress concentrations due to the geometry, and the orientation of the crack propagation with respect to the rolling direction of the plate are expected to contribute to the lack of ductility. There was no evidence to indicate that the joining method, materials, or welding procedures were inadequate. The welds appeared to perform as intended.

In general, perimeter columns severed by the aircraft wing did so at the internal stiffener or diaphragm plate associated with the spandrel connection to column. Perimeter columns hit by the plane tended to fracture along heat-affected zones adjacent to welds. Perimeter columns outside the impact zone did not exhibit this behavior.

The failure mode of spandrel connections on perimeter panels differed above and below the impact zone. At or above the impact zone, bolt hole tear-out was more common. Below the impact zone, it was more common for the spandrels to be ripped off from the panels. The change in mode may be due to shear failures as the weight of the building during collapse came down on these lower panels. There was no evidence that fire exposure changed the failure mode for the spandrel connections

With the exception of the mechanical floors, the perimeter panel column splices failed by fracture of the bolts. At mechanical floors, where splices were welded in addition to being bolted, the majority of the splices in the several recovered columns did not fail.

### E.3.2 Structural Impact Damage – Core Columns

Failure of the limited number of recovered core columns was a result of both splice connection failures and fracture of the columns themselves. One recovered core column (WTC 2, column line 801, floors 77–80) may have sustained damage as a direct result of the airplane impact; however, the welded splice to the column above survived intact.

### E.3.3 Structural Damage – Floor Trusses and Seats

In both towers, most of the perimeter panel floor truss connectors (perimeter truss seats) below the impact floors were either missing or bent downward. Above this level, the failure modes were more randomly distributed. This behavior apparently resulted from the building collapse sequence.

Failure of the welds associated with the perimeter panel floor truss connectors (perimeter seats) typically occurred as a result of the weld geometry. The component that failed was the one with the smallest cross-sectional area with respect to the high loading forces of the collapse. Typically, these were the standoff plates. However, there was no evidence to indicate that the type of joining method, materials, or welding procedures were inadequate.

Of the 31 core floor truss connectors (core seats) recovered, about 90 percent were still intact, although many were extensively damaged. Only two were completely torn from the channel. This distribution may have resulted from the process used to select recovered steel from at the salvage yards, however.

In the recovered floor trusses, a large majority of the electric resistance welds at the web-to-chord connections failed. Failure of the connection between the floor truss and the perimeter panel floor truss connectors was typically a result of tab plate weld and bolt failure.

### E.3.4 Damage to Fireproofing Due to Aircraft Impact

Pre-collapse photographs indicated that, as expected, fire-proofing was removed from pieces struck by the incoming aircraft or debris exiting the far side of the buildings. In addition, the impact caused fire-proofing and aluminum facade panels to spall off many perimeter columns which were not directly struck nor severed, but apparently suffered strong accelerations and forces otherwise transmitted through the structure. This indirect damage to the spray-applied fire resistant material (SFRM) was observed on the north and east faces of WTC 2.

A coating on the SFRM prevented the loss of the SFRM in some locations on the perimeter columns. This coating appeared as a band of white features on the SFRM wherever two aluminum panels met on the exterior columns of the buildings, becoming visible when the panels were dislodged. This may be a coating applied to protect the SFRM from moisture infiltration at the aluminum panel joints, acting to preserve the SFRM even when the SFRM was knocked off both above and below those locations.

### E.3.5 Time-Dependent Deformation of Perimeter Walls Due to Fire and Load Redistribution

Images of WTC 1 showed gross deformations of the south wall prior to final collapse. Images taken approximately 5 min prior to collapse showed inward bowing of the exterior columns, reaching an observable maximum of about 55 in. near column 316 on the 96th floor. The inward deflection appeared to extend over the entire south face of the building at this time, and was visible between the 94th and 100th floors. Photographs taken approximately 35 min prior to collapse did not show any inward bowing of the south face of WTC 1.

Approximately 18 min after the impact of the aircraft, the east face of WTC 2 exhibited inward bowing of up to 10 in. in the region of the 79th to 83rd floors. This inward bowing increased to 20 in. at 5 min before collapse of the tower.

Sagging floor slabs at the 82nd and 83rd floors were visible in window openings on the east and north faces, respectively, of WTC 2 and the positions of these slabs changed over time. This suggests a progression of failure of certain parts of the flooring in this area of the tower.

At the moment of collapse of WTC 2, the top portion of the building was found to have moved to the west as it tilted to the southeast. During this tilting, a complex kink developed at the southeast corner of the top of the building, in the region of the 106th floor. In addition, the portion of the building above the aircraft impact site twisted slightly clockwise (as viewed from above) as the collapse progressed.

### E.3.6 Fire Exposure and Temperatures Reached by the Steel

The pre-collapse photographic analysis showed that 16 recovered exterior panels were exposed to fire prior to collapse of WTC 1. None of the nine recovered panels from within the fire floors of WTC 2 were observed to have been directly exposed.

NIST developed a method to characterize maximum temperatures experienced by steel members using observations of paint cracking due to thermal expansion. The method can only probe the temperature reached; it cannot distinguish between pre- and post-collapse exposure. More than 170 areas were examined on the perimeter column panels; however, these columns represented only 3 percent of the perimeter columns on the floors involved in fire and cannot be considered representative of other columns on these floors. Only three locations had evidence that the steel reached temperatures above 250 °C. These areas were:

- WTC 1, east face, floor 98, column 210, inner web,
- WTC 1, east face, floor 92, column 236, inner web,
- WTC 1, north face, floor 98, column 143, floor truss connector

Other forensic evidence indicates that the last example probably occurred in the debris pile after collapse.

Annealing studies on recovered steels established the set of time and temperature conditions necessary to alter the steel microstructure. Based on the pre-collapse photographic evidence, the microstructures of steels known to have been exposed to fire were characterized. These microstructures show no evidence of exposure to temperatures above 600 °C for any significant time.

Similar results, i.e., limited exposure if any above 250 °C, were found for two core columns from the fire-affected floors of the towers. Note that the perimeter and core columns examined were very limited in number and cannot be considered representative of the majority of the columns exposed to fire in the towers.

Perimeter columns exposed to fire had a greater tendency for local buckling of the inner web than those known to have no exposure. A similar correlation did not exist for weld failure.

## E.4 MECHANICAL PROPERTIES

Mechanical properties of the steel were determined using tests at room temperature (for modeling baseline performance), high temperature (for modeling structural response to fire), and at high strain rates (for modeling the airplane impact). In addition, the structural steel literature and producer documents were used to establish a statistical basis for the variability expected in steel properties and for modeling steel properties as a function of temperature and strain rate for insertion into building performance models. A total of 32 distinct steels (various strengths and suppliers) were modeled in this manner.

A comparison of mechanical properties with relevant specifications and properties required by the design documents is included. The steel used in the construction of the WTC generally met the expectations of the designers and the specifications called for in the steel contracts. Approximately 87 percent of all tested steel exceeded the required minimum yield strengths specified in design documents, and approximately 13 percent of the damaged steel tested did not meet the required minimum yield strengths. The occurrence of test results below the specified minimum values is not unexpected because differences in test procedures from those in the qualifying mill tests could account for 2 ksi to 3 ksi lower values in the NIST tests, the loss of a yield point due to damage to the steel accounts for 2 ksi to 4 ksi lower values in the NIST tests in several cases, and variability exists within a heat of steel relative to the ASTM specified test location.

The yield strengths of the perimeter column steels generally exceeded their specified minimums by 10 percent to 15 percent. The tensile properties of the perimeter columns are consistent with literature estimates for average properties of construction steel plate during the WTC construction era. The number of occurrences of plates with tensile properties at or slightly below the specified minimum is consistent with the historical variability of steel strength.

The yield strengths of steels in the core columns, with a few exceptions, exceeded the specified minimum. The yield strengths of some wide-flange shapes were lower than called for in the specifications but, as stated above, this probably arose from a combination of mechanical damage that removed the yield point, differences between the NIST and original mill test report testing protocols, and variability within a heat of steel relative to the ASTM International (ASTM) specified test location. Regardless of the source, the observed distributions are accounted for in the typical design factor of safety for allowable stress design. The yield strengths of undamaged steels in the rolled core columns, however, were lower than the historical literature indicates as typical.

The strength of the steel in the floor trusses was higher than called for in the original specifications. Many of the truss steels that were specified as low strength A 36 were supplied as high-strength, low-alloy steels with much higher strengths. Laclede Steel Company’s substitution of 50 ksi yield strength steel for A 36 in the lower chord of the trusses is expected to have provided significantly improved performance at high temperature.

The limited tests on bolts indicate that their strengths were greater than the specified minimums, and they were stronger than contemporaneous literature suggests as typical.

Limited tests on recovered welds and weld material indicated that their mechanical properties and chemistry were consistent with their intended specifications.

The strain rate sensitivity and high-strain rate ductility of the perimeter and core column steels were similar to other construction steels of the WTC era. The impact toughness of steels from the perimeter and core columns, and floor trusses was consistent with literature values for the WTC construction era.

The high-temperature yield and tensile strength behavior of WTC steels was similar to behavior of construction steels from the WTC construction-era literature. The creep behavior of WTC steels was modeled by scaling WTC-era literature data using room temperature tensile strength ratios.

In summary, the steel used in the construction of the WTC towers met the expectations of the designers and the specifications called for in the steel contracts. Material substitutions of higher strength steels were common in the perimeter columns and floor trusses. The safety of the WTC towers on September 11, 2001, was most likely not affected by the fraction of steel that, according to NIST testing, did not meet the required minimum yield strength. The typical factors of safety in allowable stress design can accommodate the measured property variations below the minimum.

## E.5 PHYSICAL PROPERTIES

A number of physical properties of the structural steel from the towers were either measured or estimated. Of these, composition and microstructure were characterized for many of the recovered pieces in order to identify the specifications to which the steel was fabricated, enabling a better characterization of the mechanical properties of the steel. In addition, thermal properties were estimated as a function of temperature in order to provide input to models of the steel thermal response to the fires.

Chemical analyses of the flange, outer web, and spandrel plates of the exterior panel sections were found to be nearly identical for a given plate gauge and yield strength, as were inner web plates with yield strengths equal to 80 ksi or 100 ksi. In contrast, inner web plates with yield strengths less than 80 ksi were found to be chemically distinguishable from the other plates. These results support the contemporaneous documents stating that Yawata Steel (now Nippon Steel) produced all flange, outer web, and spandrel plates, and that inner web plates were primarily supplied domestically. The alloying practices were typical for steels of this era.

Chemistry results for the core columns varied for any given strength and shape (built-up box, rolled wide-flange). This result supports the contemporaneous documents that state numerous suppliers produced the steel to be used for these structural components. All core columns tested met chemistry specifications for one of the numerous ASTM structural steel grades available during the construction era.

Floor truss rods and chords, manufactured by Laclede Steel Co., met chemistry specifications for ASTM A 242. Contemporaneous construction documents indicated that Laclede Steel Co. routinely upgraded A 36 components to A 242 steel.

Two types of bolts were specified for construction of the towers, A 325 and A 490 bolts. Stampings on the bolt heads clearly indicated the bolt type. Chemical analysis indicates the bolts met the A 325 Type 1 chemistry specifications.

A majority of the other structural components (floor truss seats, diagonal bracing straps, gusset plates, core channels, etc.) met chemistry specifications for ASTM A 36 grade steel, which was the default steel when strengths were not specified on the design drawings.

## E.6 STRUCTURAL STEEL IN WTC 7

No steel was recovered from WTC 7; however, construction-related documents describe the structural steel as conventional 36 ksi, 42 ksi, and 50 ksi steels. The building plans called for rolled column shapes conforming to two ASTM grades: A 36 and A 572 Grade 50. Cover plates for the heaviest plates were specified as A 588 Grades 42 and 50, and A 572 Grade 42. There is a substantial literature base on the properties of these steels.

The literature of the construction period was researched in order to estimate properties and provide models of room temperature mechanical properties of the various steels. Methods developed for the WTC tower steels were used to model the high temperature mechanical performance for the building performance models of WTC 7 response to the fires.

## E.7 ISSUES

Based on the Investigation findings, NIST identified a detailed set of issues related to practice, standards, and codes that provided the basis for formulating the Investigation's draft recommendations. The Investigation team has studied practices ranging from those used during construction of the towers to newly available practices that could improve the safety and performance of high-rise buildings. The recent development and use of "fire-resistant" steel in Europe and Japan falls in the latter category.

Fire-resistant steels are reported to retain a higher fraction of their room temperature strength at temperatures expected in building fires, and are used either with or without fire protection depending on the application. If fire-resistant steels do indeed retain improved high temperature properties, then improved fire resistance would be expected even in cases where conventional fire protection has been damaged, whether during normal construction and modifications, or due to other damage as in the attack on the WTC towers.

Each issue identified by NIST was divided into three levels with between two and five categories each:

- Categories in Level 1: practices; standards, codes, and regulations; adoption and enforcement; research and development or requiring further study; and education and training.
- Categories in Level 2: all tall buildings (buildings over 10 stories in height); selected tall buildings (buildings over 10 stories in height that are at risk due to design, location, use, iconic status, contents, etc.); selected other buildings (buildings that are at risk due to design, location, use, historic/iconic status, contents, etc.).

- Categories in Level 3: related to the outcome on September 11, 2001 (i.e., could have changed the outcome); or unrelated to the outcome on September 11, 2001 (i.e., would not have changed the outcome yet is an important building and fire safety issue that was identified during the course of the Investigation).

Under Level 1, the fire-resistant steel issue is considered to include practices and research and development or requiring further study. The fire-resistant steel issue under Level 2 applies to all tall buildings and selected other buildings. Under Level 3, the use of fire-resistant steel in the WTC towers may have increased the time to collapse of the towers.

Discussion of this issue is not intended to suggest that fire-resistant steels should have been used in the construction of the WTC towers, or even that fire-resistant steels were available commercially at the time of their construction.